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MDC G-4631

COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS

JUNE 1973

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Prepared under Contract No. NAS 8-28377
by Biotechnology and Power Department
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By
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Biotechnology and Power Department

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FOREWORD

A Cost Analysis of Life Support Systems Study has been conducted by the Biotechnology and Power Department of the McDonnell Douglas Astronautics Company (MDAC), Huntington Beach, California, under Contract NAS8-28377. This project was performed for the NASA-Marshall Space Flight Center under the direction of Mr. James Moses, Deputy Chief, Life Support and Environmental Branch (S&E-ASTN-P).

The final report consists of a summary and four volumes each dealing with a specific life support system area as follows:

Title	Report Number
SUMMARY REPORT	MDC G4630
COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS	MDC G4631
COST ANALYSIS OF WATER RECOVERY SYSTEMS	MDC G4632
COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS	MDC G4633
COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS	MDC G4634

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Section 1

INTRODUCTION AND SUMMARY

1.0 INTRODUCTION

Experience indicates that when proceeding from a working prototype life support system to flight-qualified hardware, a significant increase in cost is incurred. In order to assist NASA in long-range planning and allocation of resources in a cost effective manner in support of earth orbital programs, a methodology was developed to predict the relevant contributions of the more intangible cost elements encountered in the development of flight-qualified hardware based on an extrapolation of past hardware development experience. Major items of costs within life support subsystems were identified and related to physical and/or performance criteria. Cost and performance data from Gemini, Skylab, and other aerospace and biotechnology programs were analyzed to identify major cost elements required to establish cost estimating relationships for advanced life support subsystems. This report deals with the three leading carbon dioxide concentration systems, namely 1) the Molecular Sieves CO_2 Concentrator, 2) the Hydrogen-Depolarized Concentrator, and 3) the Regenerable Solid Desiccant Concentrator.

The three leading carbon dioxide concentrators were quantitatively evaluated. System characteristics, including process flows, performance and physical characteristics were also analyzed. Additionally, the status of development of each of the systems considered and the required advance technology efforts required to bring conceptual and/or preprototype hardware to an operational prototype status were defined. The equipment classifications used based on the degree of refinement were as follows: 1) working model, 2) low-fidelity prototype, 3) high-fidelity prototype, and 4) flight-qualified system.

The most cost effective development approach was discovered to be with the programs that initially used working models and subsequently low-fidelity prototypes to verify concept workability. The further continuation of the development of the best approaches in the advanced research and technology phase from the low-fidelity to high-fidelity level had the potential of further reducing costs prior to committing funds to produce flight-qualified hardware. It was apparent that the high-fidelity hardware should be included in the advanced research and technology phase to provide the data required to minimize design changes in the flight production and qualification program. Design changes that occur too late in the development cycle will significantly escalate costs. The advanced research and technology phase, when effectively used, as previously discussed, has the overall effect of improving the production hardware development schedule and reducing the total program cost, including the expense of hardware, system certification, and testing.

The system costs were determined based on the summation of the average derived cost of each individual component for a given subsystem configuration. The system program costs were proportioned based on past recorded Gemini program experience. Cost of low- and high-fidelity water recovery system prototypes were also evaluated and found to average approximately 5% and 10%, respectively, of the cost of flight-qualified units. Resulting cost data agreed favorably with past equipment costs for other low- and high-fidelity prototype hardware developed in advanced research and technology programs. Estimates of the cost of a flight-qualified molecular sieves CO_2 concentrator also agreed favorably with the actual cost of the Skylab molecular sieves. The cost analysis of carbon dioxide concentrators is is presented in the following sections.

Cost Estimating Techniques

Cost Estimates of Carbon Dioxide Concentrators

Conclusions

Section 2

COST ESTIMATING TECHNIQUES

Cost estimations were established for both low- and high-fidelity prototypes and flight-qualified-type carbon dioxide concentrators utilizing the methodology discussed below.

2.1 COST ESTIMATES OF CARBON DIOXIDE CONCENTRATOR PROTOTYPES

The cost of low-fidelity carbon dioxide concentrator prototypes was found to depend on its degree of sophistication and utilization of available space hardware and/or commercial components. A cost estimate approximately equal to half that of a corresponding high-fidelity prototype was allocated to low-fidelity prorotypes. High-fidelity prototypes were assumed to be similar in construction to the first test system produced in a flight program which has not undergone any qualification or reliability testing. The cost of the high-fidelity prototype was obtained by excluding those cost items which are pertinent solely to flight articles. Cost of low- and high-fidelity prototypes constituted 5% and 10%, respectively, of the cost of a corresponding flight-type system. A more detailed discussion of prototype cost estimating is presented in Report No. MDC G4630, "Cost Analysis of Life Support Systems - Summary Report".

2.2 COST ESTIMATES OF FLIGHT-QUALIFIED CARBON DIOXIDE CONCENTRATORS

The CO_2 concentrators cost estimating techniques were developed by 1) identifying the physical and performance characteristics of each of the system components, 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered, and 3) the summation of equations for respective system components to establish the total system cost estimating. The U. S. Bureau of Standards Consumer Price Index was used to account for inflation and economic escalation.

The methodology used in the development of CER's is as follows:

1. The components were analyzed to determine which physical or performance characteristics might prove useful as predictive variables.

2. Costs were arrayed graphically against the candidate variables either singly or grouped. The most promising of these arrays were selected on the basis of a subjective analysis which considers the appropriateness of the variables, the form and slope of the curves, and the relative aspects of the component costs.

The derivation of a typical life support component CER is presented in detail in Report No. MDC G4630. Individual CER's for respective system components were summed up to establish the total system cost estimation. The validity of derived CER's, summarized in Table I, was verified when they were applied to a number of Skylab components and were found to agree favorably with actual cost data.

A system schematic and a component identification list were prepared for each of the three CO_2 concentrators. System and process descriptions, including system performance and characteristics, were also given. The physical and performance parameters were identified for use in formulating the cost estimating relationships. Recurring CER's were then developed and computed for each of the system subassemblies and summed up to obtain the integrated system recurring cost estimates. The system's non-recurring CER's were computed on an integrated system basis. The major influencing parameter for the non-recurring CER's was found to be the number of component types in the system. A validity check was made by comparing the molecular sieves considered in this study and that developed for Skylab. Considering the differences in size and capacities of the two units, the results of the study indicated that the methodology used is valid and the cost estimates are reasonably accurate. Table II summarizes the total cost per flight-type CO_2 concentrator, including recurring and non-recurring,

Table I

CARBON DIOXIDE CONCENTRATORS

RECURRING COST ESTIMATING

	ASSEMBLY	COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)
(1)	CO_2 ACCUMULATOR	$C = 18,634\ V^{0.377} + 2959\ W_{oca}$
(2)	COMPRESSOR/AIR BLOWER	$C = 38.2\ P^{0.942} + 2192\ W_{occ}$
(3)	SOLID DESICCANT CANISTERS	$C = 15,865\ W_{CAN}^{0.267}\ Q_c^{0.89} + 2959\ W_{ocd}$
(4)	SOLID DESICCANT CANISTERS WITH BUILT-IN PLATE-AND-FIN HEAT EXCHANGER	$C = 158.65\ (100\ W_{CAN}^{0.267} + W_{HX}^{0.267}\ N_P^{1.905})\ Q_{HX}^{0.89} + 2959\ W_{ocdh}$
(5)	HEAT EXCHANGER CONDENSER	$C = 159\ W_{HX}^{0.267}\ N_P^{1.905} + 2959\ W_{och}$
(6)	TIMER AND CONTROLS	$C = 4795\ (W_T + W_{oct})$
(7)	ELECTRO-CHEMICAL CELL MODULE	$C = 400\ W_M + 2192\ W_{oce} + 2000$

TOTAL HARDWARE COST $\quad C_T = \sum_{Q=1}^{N} F_A F_I \left(\sum_{I=1}^{M} C_I\right) Q^{1-B}$ $\quad$ Dollars

Where,

N = No. of Units Purchased

F_A = Component Assembling Factor

F_I = Assembly Integration Factor

M = No. of Components in Assembly

C_I = Component Fabrication Cost

B = Learning Curve Slope

as a function of the number of units produced which result from the application of an average 93% learning curve to the recurring items.

Table II - Total Cost of Flight Units Vs.
Number of Units Produced

Number of Flight Units Developed	Molecular Sieves Concentrator	Hydrogen Depolarized Concentrator	Regnerable Solid Desiccant Concentrator
1	7,194,558	6,113,187	5,999,964
2	4,350,688	3,529,718	3,424,306
3	3,324,367	2,619,529	2,521,779
4	2,873,584	2,197,916	2,103,006
5	2,564,309	1,929,580	1,834,018
10	1,911,258	1,359,975	1,271,433
40	1,324,482	871,849	794,853

2.3 COST ELEMENT STRUCTURE

The cost element structure, comprising the detailed recurring and non-recurring cost function, provides visibility of the total project expenditures and permits identification of the significant project costs. The definition of cost-related terms used in this report is given in Section 2.5.

Table III presents a breakdown of typical life support system expenditures, as encountered in the Gemini Program, divided in the respective recurring and non-recurring items. The major recurring cost item is that of flight hardware production. The major non-recurring costs are those related to Design, AGE, and Prime Contractor's specification and procurement efforts.

TABLE III - REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN

NON-RECURRING	%	RECURRING	%
Design	16.68	Flight Hardware Production	54.56
Subcontractor General & Administrative	8.62	Subcontractor G&A	9.22
Subcontractor Fee	3.62	Subcontractor Fee	3.88
Program Management	1.24	Program Management	1.36
System Engineering	5.25	Sustaining Engineering	1.96
Development Test	3.44		
Qualification Test	2.54		
Reliability Test	4.09		
AGE	18.45		
Tooling	3.87	Sustaining Tooling	1.69
Non-accountable Test Hardware	1.67		
Specifications, Vendor Coordination and Procurement Expenses	13.62	Specifications, Vendor Coordination and Procurement Expenses	15.49
System Integration	8.36	System Integration	7.15
Prime's Testing	8.17	Minor Subcontracts	4.69
Minor Subcontracts	0.38		
TOTAL	100 %		100 %

2.4 EFFECT OF INFLATION ON COST ESTIMATES

A major inherent feature of the methodology which is highly critical to the accuracy of the results obtained pertains to inflation and economic escalation. Since computed CER's are based on specific year dollars, they must be inflated to the proper year in order to obtain realistic future program values. Due to the lack of a specific aerospace price index, the yearly dollar value adopted in this report was considered to correspond to the Consumer Price Index shown in Figure 1, based on data published by the U. S. Bureau of Statistics.

2.5 COST-RELATED DEFINITIONS

The terminology used in this study is that practiced by the McDonnell Douglas Corporation. In order to assist users of the report who are familiar with different terms or groupings of cost-related activities, the following definitions are presented.

1. Engineering Design - involves the design and analysis of individual components and assemblies in the life support system.

2. Program Management - relates to planning, organizing, directing and controlling the project. Includes scheduling deliveries, coordinating changes and monitoring problem areas.

3. System Engineering - involves system design as opposed to component or assembly design. Includes design, analysis design support, and total system non-separable hardware design and integration effort.

4. Development Testing - involves testing with breadboard and prototype hardware that is required to evaluate component and assembly design concepts and performance.

5. Qualification Testing - deals with formal qualification testing to ensure that components and assemblies provided meet mission performance and design requirements.

6. Reliability Testing - includes component and assembly life cycle and failure analysis testing to ensure operation of the system for the required mission duration.

7. Tooling - involves the design, fabrication and maintenance of component and assembly tools.

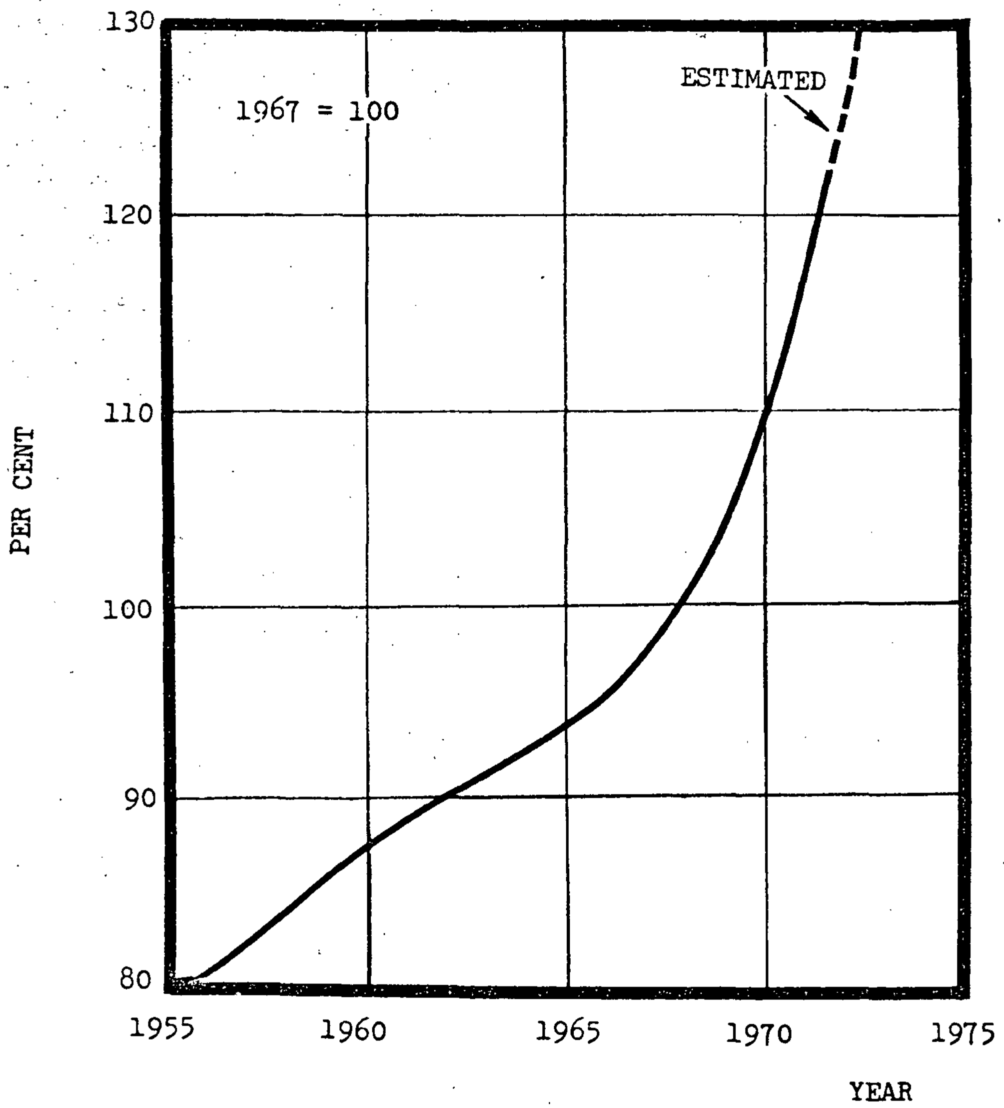

FIGURE 1 - Consumer Price Index
(Source: U. S. Bureau of Labor Statistics)

8. Non-Accountable Test Hardware - includes prototype units, breadboards, operational mock-ups and other non-deliverable development hardware items.

9. Aerospace Ground Support - includes design and fabrication of system test and servicing, system handling and checkout and hardware necessary during acceptance testing and launch operations.

10. Sustaining Engineering - includes incorporation of changes, modifications to design and contractor's project engineering design.

11. Subcontractor General and Administrative - includes overhead expenses charged as fixed percentages of all other costs.

12. Subcontractor Fee - involves the fee charged by the subcontractor as negotiated at beginning of the contract.

13. Minor Subcontractor - includes procurement costs for minor valves, lines and other required miscellaneous parts.

14. Prime Contractor Costs - include specifications, vendor coordination, procurement and documentation expenses.

15. Recurring Costs - recurring expenditures are divided into the Prime Contractor and Major Subcontractor costs. The Prime Contractor efforts involve primarily the incorporation of the life support systems into the spacecraft. The Major Subcontractor costs are broken into Sustaining Engineering, Tooling and System Production. The System Production expenditures are segregated into subsystems and these are in turn segregated into components.

16. Non-recurring - non-recurring expenditures for each life support subsystem are segregated into Prime Contractor and Major Subcontractor efforts. The Prime Contractor effort involves specification, coordination and integration of the system into the spacecraft. The Major Subcontractor effort is divided into Design and Development, AGE, Program Management and System Engineering, Test Operations and Hardware. The Design and Development costs are segregated into major subsystems.

Section 3

COST ESTIMATES FOR CARBON DIOXIDE CONCENTRATORS

Cost estimating relationships were derived for the following CO_2 concentrator systems:

1. Molecular Sieves CO_2 Removal System
2. Hydrogen-Depolarized CO_2 concentrator
3. Regenerable Solid Desiccant

The molecular sieves systems have undergone more development than any other CO_2 concentrator. A number of molecular sieves units have been developed and tested for extended durations in manned ground simulator tests. Additionally, a flight-type molecular sieves CO_2 removal unit has been developed for Skylab. Near-complete cost data are available for this unit. The Skylab unit varies from that considered in this report in that it requires no collection of CO_2 and thus does not include a CO_2 accumulator. The Skylab CO_2 concentrator is regenerated by desorbing the carbon dioxide and moisture collected by the beds to space vacuum. A hydrogen-depolarized CO_2 concentrator (HDC) is currently under development for use in the Space Station Prototype (SSP) program. HDC's have been under continuous development by TRW, Inc., and Life Systems, Inc., under NASA-ARC sponsorship for the last six years. The HDC, when brought to a high-fidelity prototype as expected under the SSP program, would cost up to 20% less than a comparable molecular sieves system. In addition, the HDC has superior performance characteristics as it potentially can provide <3 mm Hg of CO_2 in the cabin atmosphere as compared to 3 mm Hg to 5 mm Hg provided by the state-of-the-art molecular sieves system.

The Regenerable Solid Desiccant System is in a lesser state of development than the other two systems evaluated. The system utilized a kind of regenerable solid amine resin that absorbs CO_2 in the presence of water vapor, which alleviates the need for silica gel pre-dryers as required in the case of

molecular sieves. The system thus requires fewer components and a smaller air blower than molecular sieves. The system simplicity should also be manifested in higher reliability and lower cost. A limited number of solid disiccant units have been developed. One unit was developed by General American Transportation Company, in which a proprietary resin called GAT-O-SORB was used. The unit was vacuum-desorbed and did not require the collection of desorbed CO_2. Currently, a vacuum-desorbed regenerable solid desiccant unit is being developed for possible application to the Shuttle spacecraft. Another unit, which is steam-desorbed, was built by Hamilton-Standard and tested for approximately 60 days in the NASA 90-day manned test. The 90-day unit included a CO_2 accumulator and delivered the collected CO_2 to the CO_2-reduction system. However, the steam-desorption mode of operation resulted in introducing complexities to the system as well as high power consumption and heat rejection requirements. For these reasons, a heat-desorbed regenerable solid desiccant system was used in this report. Such a system should be capable of collecting CO_2 and delivering it to a CO_2 reduction system. No technological problems exist that would hinder the operation of this system which resembles the GAT-O-SORB system except that it requires a condenser for the removal of entrained moisture from the desorbed CO_2 prior to its delivery to the accumulator. CO_2 concentrator system criteria for the three systems considered are presented in Table IV which also presents the relative characteristics, operational differences and status of each of the three systems.

A discussion of each of the three carbon dioxide concentrator systems and detailed cost estimates of the processes involved are presented in the following paragraphs.

TABLE IV - COMPARISON OF CARBON DIOXIDE CONCENTRATION SYSTEMS

System Characteristics	Molecular Sieves CO_2 Concentrator	Hydrogen Depolarized CO_2 Concentrator	Regenerable Solid Desiccant CO_2 Concentrator
Crew Size	6 men	6 men	6 men
CO_2 Produced, Average	2.2 lbs/man-day	2.2 lbs/man-day	2.2 lbs/man-day
CO_2 Partial Pressure, Nominal	3.0 mmHg	1.0 mmHg	1.5-3.8 mmHg
Heating Fluid	Coolanol 35	None	Coolanol 35
Heating Fluid Temperature	300-350°F	--	180-200°F
Coolant	Coolanol 35	Air	Coolanol 35
Cooling Fluid Temperature	50-65°F	65-75°F	60-80°F
CO_2-Accumulator Pressure	30-40 psia	30-40 psia	30-40 psia
System Operation	1. Silica gel dries air to -50°F dp 2. Cool molecular sieves absorb CO_2 3. Beds thermally regenerated	1. CO_2 electrochemically transferred from anode to cathode. 2. H_2 added to produce power and water.	1. No air predrying req'd. 2. Chemical absorption enables system to operate at low CO_2 concentrations.
System Status/Availability	1. Prototypes developed and tested, incl. that in NASA 60 & 90 Day Tests 2. Vacuum-desorbed unit will be flown on Skylab in 1973.	1. TRW, Inc. & Life Systems,Inc. developed units for 6 years. 2. Life Systems, Inc. will deliver a 6-man system in 1973. 3. Hamilton Standard is developing a back-up system under SSP Program.	1. GAT-O-SORB, a 2-man vacuum-desorbed system was developed by General Amer. Transportation Co. 2. A steam-desorbed solid amine system was tested in NASA 90-Day Test. 3. A vacuum-desorbed unit is being developed for Shuttle application.
Operational Problems	None anticipated.	Integrated manned test of system required to define operational problems	A development of a thermal desorbed unit, with a CO_2 accumulator, is required.

3.1 MOLECULAR SIEVES CARBON DIOXIDE REMOVAL SYSTEM

System Description:

The molecular sieves CO_2 removal system is used to remove the CO_2 from the cabin atmosphere. The carbon dioxide is collected in an accumulator and then delivered to the oxygen recovery system.

A schematic of a molecular sieve system patterned after the unit under development for the Space Station Prototype program is shown schematically in Figure 2. The system is comprised of the following basic components: 1) air blower, 2) two silica gel beds, with each bed consisting of two canisters in parallel, 3) two molecular sieve beds, each consisting of two canisters in parallel, 4) heat exchangers, 5) pump, 6) accumulator, and 7) timer, manifolds and sequence control valves. A detailed listing of the components is given in Table V.

Function of the system is as follows: cabin air is drawn by the circulation blower through the adsorbing silica gel bed where the moisture in the air is removed to a dew point of -50° to -70F. The flow then enters into the heat exchanger cooling it to 40° to 50°F. The cool, dry air then passes through the adsorbing molecular sieve bed where the CO_2 is removed. Most of the dry, CO_2-free gas is discharged into the cabin. The remaining gas is passed to the desorbing silica gel canister which has been heated to approximately 300°F with the heating fluid. This dry gas flow is saturated with the water being driven off the beds by the heat and then delivered to the cabin. The desorbing molecular sieve bed is meanwhile being regenerated, heated to 300°F with the heating fluid and evacuated with a vacuum pump. The pump delivers the desorbed CO_2 to an accumulator for storage and subsequent delivery to the oxygen recovery system. Excess CO_2 may also be vented overboard via a relief valve.

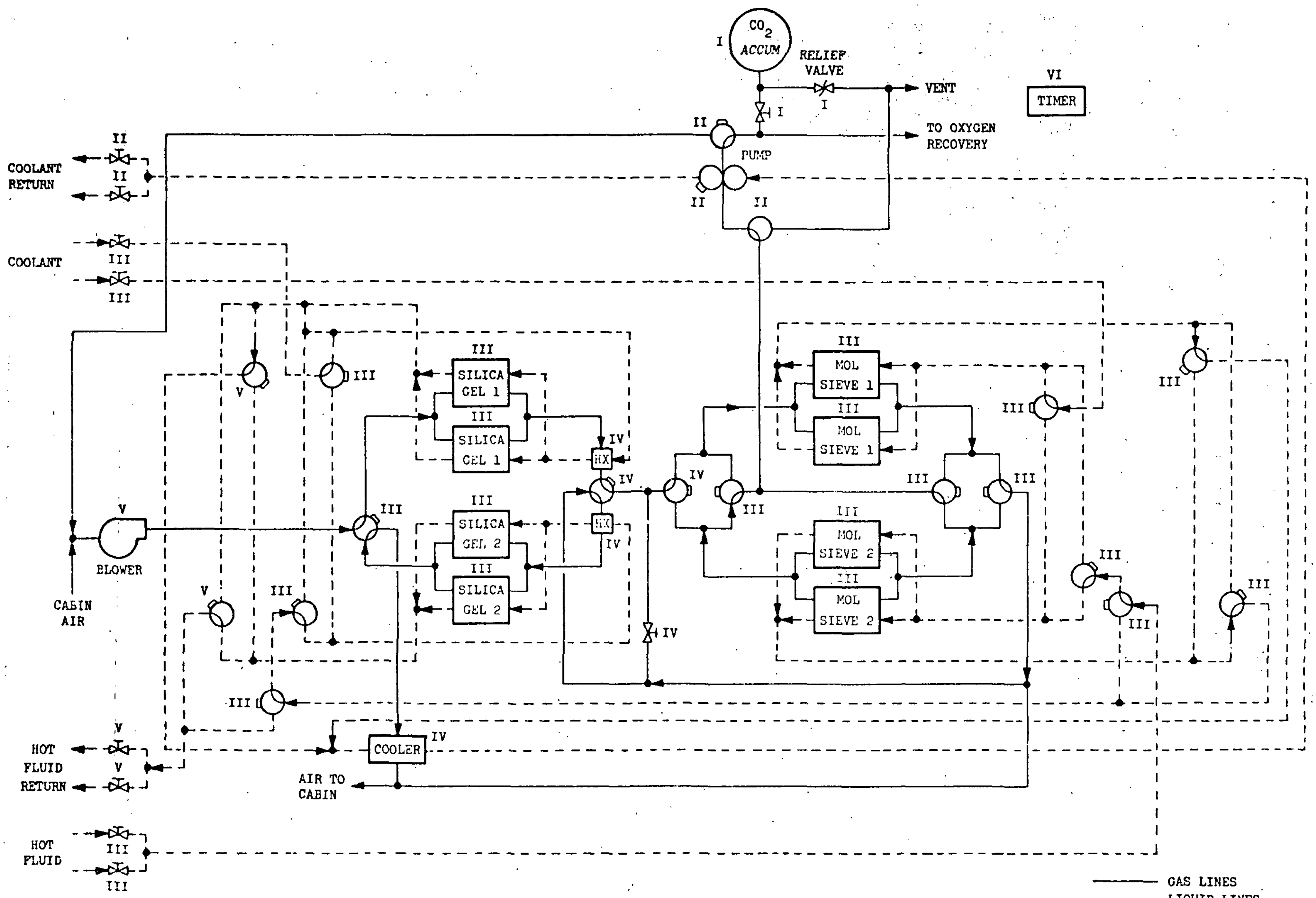

Figure 2. MOLECULAR SIEVES CARBON DIOXIDE REMOVAL SYSTEM SCHEMATIC

After 30 minutes of desorption, the coolant is pumped to the desorbing beds to cool them for 15 minutes before cycling to the adsorption cycle. The timer then sequences the valves to divert the cabin flow through the regenerated beds and place the beds now requiring regeneration on desorption cycle. Heating fluid will then flow through the desorbing beds and the cycle is repeated. The time for a complete adsorption, desorption, and cooling cycle is 90 minutes. The sequencing of the control valves is accomplished by a timer.

TABLE V - MOLECULAR SIEVE SYSTEM COMPONENTS LIST

COMPONENT	QUANTITY	SPARES	UNIT WEIGHT (LBS.)
Valve, Shut-off, Manual, Low Press	1	1	2.4
Valve, Shut-off, Manual	4	3	.5
Valve, 4-Way, Electrical	2	3	4.4
Valve, Vacuum, 3-Way, Electrical	2	3	4.6
Valve, Shut-off, Elect., Man. Override	2	1	2.7
Valve, Vacuum, 3-Way, Manual	1	1	3.5
Valve, Press., Relief	1	1	2.5
Valve, Press., Control	1	2	2.2
Valve, 3-Way, Electrical	1	2	.7
Canister, Silica Gel	4	2	66
Canister, Molecular Sieve	4	2	68.2
Blower, CO_2 Removal	2	2	14.0
Compressor, CO_2	1	3	38.0
Heat Exchanger	3	1	16.0
Accumulator, CO_2	1	0	35.0
Timer	1	2	8.0
Valve, Vacuum, 3-Way, Electric	2	3	2.0
Controller, M. S. Heater	4	0	3.0
Sensor, M. S. Temperature	4	0	.1
Valve, Shut-off, Manual High Flow	8	0	3.9
Valve, 3-Way, Electrical	10	3	4.7
Measurement Switching Unit, OCS	1	0	15.6
Measurement Unit, OCS	1	0	12.1
TOTALS	61	35	-

SYSTEM PERFORMANCE AND CHARACTERISTICS:

The physical, performance, and interface characteristics of the molecular sieves CO_2 removal system are as follows:

Crew Size	= 6 Men
CO_2 Produced, average	= 2.2 Lbs/Man-Day
CO_2 Produced, Maximum	= 3.11 Lbs/Man-Day
Design CO_2 removal rate	= 1.07 Lbs/Hr
Atmospheric Flow Rate	= 75 CFM
Inlet CO_2 partial pressure, maximum	= 2.86 mmHg
CO_2 delivery purity, percent	= 98
Coolant flow rate	= 1100 Lbs/Hr
Heating fluid flow rate	= 925 Lbs/Hr
Coolant inlet temperature, maximum	= 65 °F
Hot Fluid inlet temperature, minimum	= 275 °F
CO_2 delivery pressure to CO_2 Reduction Subsystem	= 30-40 Psia
Electrical Power, D.C.	= 25 Watts
Electrical Power, A.C.	= 754 Watts
Total System Volume	= 63 Ft^3

Performance characteristics of the system's major components are as follows:

1. Air Blower:

Air Flow	= 75 CFM
Pressure Rise at 10 PSIA	= 9.2 in. H_2O
Power, A.C.	= 330 Watts

2. Silica Gel Bed:

Air flow	= 75 CFM
Gas side ΔP at 10 PSIA	= 1.62 in. H_2O
Cyclic water capacity	= 1.30 Lbs
Cold coolant flow	= 330 Lbs/Hr
Hot coolant flow	= 462 Lbs/Hr
Half-cycle time	= 30 Minutes
Cold coolant inlet temperature, maximum	= 65 °F
Hot coolant inlet temperature, minimum	= 200 °F
Coolant side ΔP	= 1 PSI

3. Molecular Sieve Bed:

Air flow	= 75 CFM
Gas side ΔP at 10 PSIA	= 1.30 in. H_2O
Cyclic CO_2 capacity	= 1.22 Lbs/Hr
Cold coolant flow	= 220 Lbs/Hr
Hot coolant flow	= 462 Lbs/Hr
Half cycle time	= 60 Minutes
Cold coolant inlet temperature, maximum	= 65 °F
Hot coolant inlet temperature	= 275 - 300°F

4. Heat Exchangers:

Gas flow	= 75 CFM
Inlet/outlet temperature, maximum	= 240/115°F
Gas side ΔP at 10 PSIA	= 0.3 in. H_2O
Coolant flow	= 1100 Lbs/Hr
Coolant inlet temperature, maximum	= 80 °F
Coolant side ΔP	= 1.0 PSI

5. CO_2 Pump

CO_2 Flow	= 1.22 Lbs/Hr
Inlet pressure, average	= 0.5 PSIA
Outlet pressure, maximum	= 40.0 PSIA
Inlet temperature	= 100 °F
Power, A.C.	= 420 Watts

6. CO_2 Accumulator:

Operating pressure	= 30-40 PSIA
CO_2 feed rate, average	= 1.33 Lbs/Hr
CO_2 delivery rate, average	= 1.60 Lbs/Hr
Net cyclical CO_2 capacity	= 0.475 Lbs

Cost Estimating Relationships:

The molecular sieve system components have been grouped in six groups, designated as I through VI, as shown in the system schematic, Figure 2. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index, shown in Figure I, was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's

1. CO_2 Accumulator:

The CO_2 accumulator CER, based on a CER developed for high pressure gaseous containers, is given as follows:

CO_2 accumulator fabrication cost $C = 18{,}634V^{0.377} + 2959\ W_{oc}$ dollars

where, V = volume of the accumulator, Ft^3, and

W_{oc} = weight of other components, lbs.

The other components denote the valves associated with the operation of CO_2 accumulator. An assembly integration factor is used at the assembly level to account for necessary piping and packaging.

Substituting the values for the variables in the above equation, where $V = 9.1 Ft^3$ and $W_{oc} = 4.5$ lbs., yields:

$$C = 18{,}632 \times 2.3 + 2959 \times 4.5 = 56{,}169 \text{ dollars}$$

2. CO_2 Compressor:

The influencing parameter in the CO_2 compressor fabrication is the electrical power input to the unit. The CER is given as follows:

CO_2 compressor fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars

where, P = electrical power input to the compressor, watts, and

W_{oc} = weight of other components, lbs.

for the CO_2 compressor,

$P = 420$ watts, and

$W_{oc} = 12.0$ lbs.

Substituting these values in the above equation yields the following:

$$C = 38.223 \times 300 + 2192 \times 12 = 37{,}771 \text{ dollars}$$

3. Silica gel and molecular sieve canisters.

A CER derived for LiOH canisters was modified and used the silica gel and molecular sieve canisters. The two types of canisters were considered essentially identical for cost estimating purposes. The CER is given as follows:

Canisters fabrication cost $C = 15{,}865\ W_{can}^{0.267} Q^{0.89} + 2959\ W_{oc}$ dollars

where, W_{can} = average canister weight, lbs.

Q = number of units used, and

W_{oc} = other components weight, lbs.

Substituting the corresponding values of the variables in the above equation, where W_{can} = 67.1 lbs., Q = 8, and W_{oc} = 66.2 lbs., yields:

$$C = 15,865 \times 3.08 \times 6.4 + 2959 \times 66.2 = 508,617 \text{ dollars}$$

4. Heat Exchangers

The following CER is used to evaluate the molecular sieve system heat exchangers fabrication cost:

$$C = 159\ W^{0.267} N_p^{1.905} Q^{0.89} + 2959\ W_{oc} \text{ dollars}$$

where, W = heat exchanger weight = 16.0 lbs.,

N_p = number of ports per heat exchanger = 4,

Q = number of heat exchangers used = 3, and

W_{oc} = weight of other components = 11.4 lbs.

Substituting the values of the variable in the CER yields:

$$C = 159 \times 2.1 \times 14.05 \times 2.66 + 2959 \times 11.4 = 46,212 \text{ dollars}$$

5. Air Blower:

The same CER used for the CO_2 compressor is applied to the air blower. Thus, air blower fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars,

where,

P = electrical power input to the air blower = 330 watts, and

W_{oc} = other components weight = 17.2 lbs.

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 240 + 2192 \times 17.2 = 46,870 \text{ dollars}$$

6. Timer and controls:

The CER used for the timer and associated controls fabrication cost was based on CER's for similar equipment encountered in Contract NAS9-9018, and is given as follows:

Timer and controls fabrication cost $C = 4795(W + W_{oc})$ dollars,

where,

W = timer weight = 8.0 lbs., and

W_{oc} = other components weight = 27.7 lbs.

substituting the values of variables in the CER yields:

$C = 4795 \times 35.7 = 171{,}182$ dollars

Molecular Sieve System's Recurring CER:

The integration costs of components and subassemblies into the molecular sieve system are obtained by the use of integration factors derived in the NAS9-9018 study and given in the following equations:

a. Subassembly fabrication cost S_i = 1.1 x component fabrication cost

b. First unit assembly cost = $1.833 \times \sum_{i=1}^{n} S_i$

Additionally, the total hardware cost is estimated through the utilization of the following learning curve formula:

$$C_T = \sum_{Q=1}^{n} C_F \quad Q^{(1-b)}$$

where

C_T = Total hardware cost

n = Quantity of hardware purchased

C_F = First unit cost

b = Learning curve slope

Since labor and materials have been added together, the learning curve slope, b, is derived as a composite of the 90% learning experienced on labor and the 95% experienced for materials. The resulting learning curve is a 93% curve (b = 0.1047). C_F, the first unit cost, can be for one assembly or for the total system. n, the quantity of hardware, is a mission parameter and must include test hardware, flight hardware, and spares.

Applying the above equations, then:

$$\text{First unit cost } C_F = 1.833 \times 1.1 \times (56{,}169 + 37{,}771 + 508{,}617 + 46{,}212 + 46870 + 171{,}182)$$

$$= 2.016 \times 866{,}821$$

$$= 1{,}747{,}511 \text{ dollars}$$

and, assuming the production of two flight-type units, one for testing and backup and the second for actual flight, then the total hardware recurring cost is given by:

$$C_T = 1{,}747{,}511 \times (2)^{1-0.1047} = 3{,}251{,}021 \text{ dollars}$$

Non-Recurring CER's

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates utilize the cost breakdown ratios identified in Table II, which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

System design cost C = 34,935N + 102,942 dollars

The molecular sieve system comprises 23 component types as shown in Table V accordingly,

System design cost C = 805,505 + 102,942 = 908,447 dollars

Values of other non-recurring cost items are listed in Table VI, which also shows the breakdown of recurring cost items based on the production of four flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE VI - MOLECULAR SIEVE SYSTEM COST BREAKDOWN

NON-RECURRING		RECURRING	
System Engineering Design	908,447	Flight Hardware Production	1,771,627
Subcontractor General and Administrative	469,667	Subcontractor G&A	299,404
Subcontractor Fee	197,133	Subcontractor Fee	125,785
Program Management	68,134	Program Management	44,291
System Engineering	286,160	Sustaining Engineering	63,778
Development Test	187,140		
Qualification Test	138,084		
Reliability Test	222,566		
AGE	1,004,742		
Tooling	210,760	Sustaining Tooling	54,921
Non-accountable Test Hardware	90,845		
Specifications, Vendor Coordination and Procurement Expense	742,201	Specifications, Vendor Coordination and Procurement Expense	503,142
System Integration	455,131	System Integration	232,083
Prime's Testing	445,139		
Minor Subcontracts	20,894	Minor Subcontracts	152,360
TOTAL	5,447,047		3,247,391

Total molecular sieve system cost = 5,447,047 + 3,247,391
= 8,694,438 dollars

3.2 HYDROGEN DEPOLARIZED CO_2 CONCENTRATOR

Process Description:

The hydrogen-depolarized cells are basically electro-chemical concentration cells which employ an aqueous carbonate electrolyte to transfer carbon dioxide from the cathode side of the cell, where CO_2-laden cabin atmosphere is introduced to the anode side. Hydrogen is introduced at the anode side of the cell. The overall chemical and electrochemical reactions occurring in the cell are as shown in Figure 3.

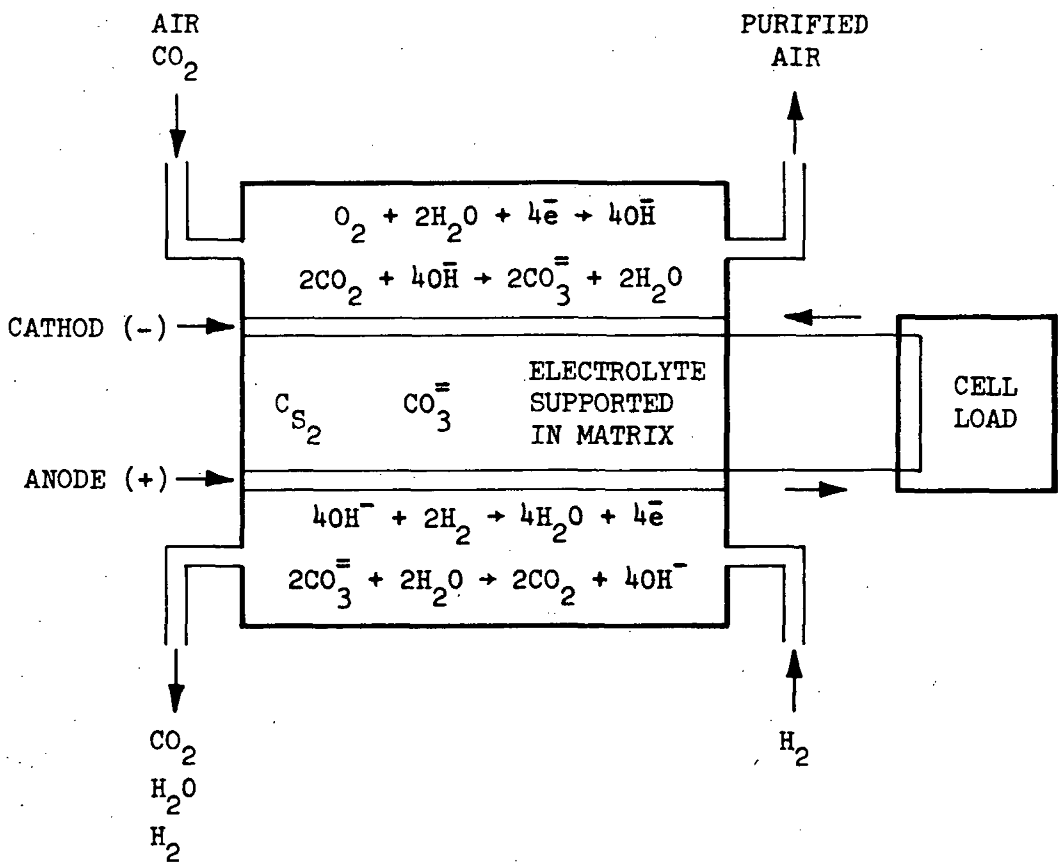

FIGURE 3. HYDROGEN DEPOLARIZED CELL

The reaction of oxygen and water forms basic hydroxyl ions (OH^-), which have an affinity for the acidic carbon dioxide. Any carbon dioxide which passes over the electrolyte, now rich in hydroxyl ions, reacts to form carbonate ions ($CO_3^=$). At the opposite electrode (anode) the reaction of hydrogen and hydroxyl ions to form water causes the electrolyte to be deficient in hydroxyl ions. Thus, carbon dioxide is given off, completing the transfer of carbon dioxide from the oxygen atmosphere to the hydrogen atmosphere. Hydrogen is available to the module as a waste product from the water electrolysis module, thereby permitting the concentrator to be operated in the hydrogen depolarized mode. In this mode of operation, the unit generates power much as a fuel cell and has the capability of supplying electrical power to other portions of the system if desired.

The hydrogen-depolarized CO_2 concentrator (HDC) module is comprised of a number of cells similar in construction to that shown in Figure 4. Each cell consists of two porous electrodes separated by a porous matrix containing an aqueous solution of cesium carbonate (Cs_2CO_3). Plates adjacent to the electrodes provide passageways for distributing the gases over the electrode surface.

The necessary number of hydrogen-depolarized cells are to be series connected. NASA tests have indicated that uniform distribution of hydrogen flow to hydrogen-depolarized cells could not be continuously achieved when the cells were in a parallel H_2 flow configuration. On the other hand, when a series configuration was used in which the first of ten cells received pure hydrogen and the last cell received approximately 70 percent hydrogen and 30 percent carbon dioxide, a stable performance was obtained. Cesium carbonate was found to be much more desirable in the CO_2 collection application than other electrolytes with lesser solubility in water. Electrochemical devices that employ aqueous electrolytes are especially sensitive to water balance. When the electrolyte becomes too concentrated as a result of a water imbalance, precepitates form at the anode of the cell, reducing the cell voltage and CO_2 transfer rate and may even result in gas crossover from anode to cathode. Consequently, electrolytes with high solubility in water are favored.

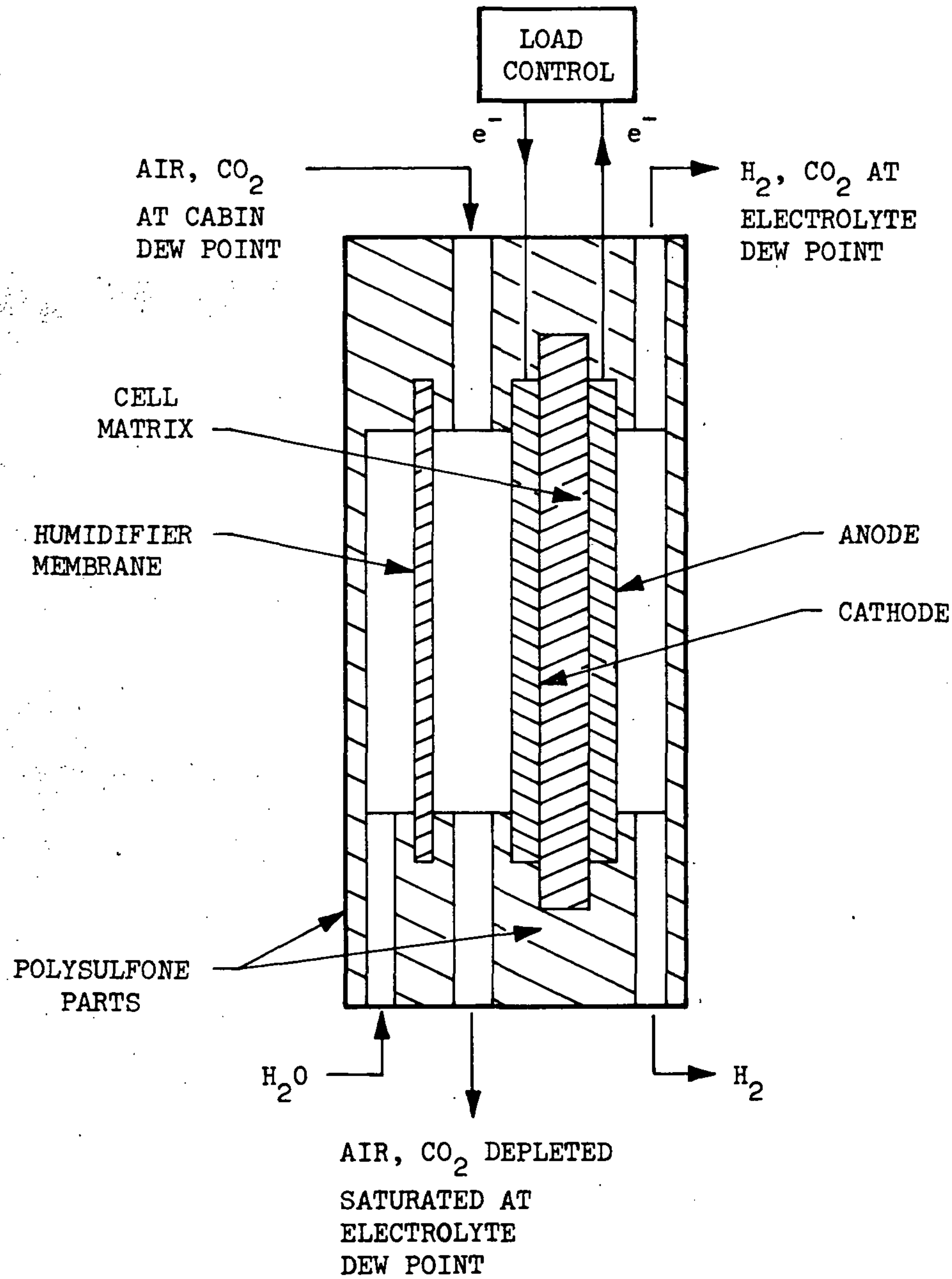

FIGURE 4. HYDROGEN-DEPOLARIZED CELL SCHEMATIC

A schematic of the HDC is shown in Figure 7. The system is comprised of the following major components: 1) the hydrogen-depolarized cell module, 2) water accumulator, 3) process air blower, 4) air heater, and 5) cooling air blower. A detailed listing of the system components is given in Table VII.

Function of the system is as follows: cabin air is drawn by the process air blower, through a particulate filter and delivered to the cathode side of the HDC module. The purified air is returned to the cabin through a filter which collects electrolyte mist entrained in the air stream. Hydrogen sensors are used to monitor trace hydrogen levels in the purified air. The anode side is provided with hydrogen from the oxygen recovery system. The CO_2 transferred from the cathode and the unreacted hydrogen are then delivered to the CO_2 reduction system. A nitrogen line, from the atmospheric control system, provides nitrogen to purge residual hydrogen from the system following system shutdown. The process air is humidified as follows: when the air enters the cathode compartment having a dew point lower than that of the original charge concentration, H_2O is transferred from the electrolyte in the humidifier and the cell matrix to the air. As H_2O is lost to the process air, the concentration of electrolyte increases and its volume decreases. Only the humidifier cavities are connected to an external supply of H_2O which, therefore, becomes the source of H_2O used for internal humidification. The decrease in liquid volume in the humidifier cavities causes H_2O to be drawn into the cavities from an external H_2O accumulator. The accumulator is cyclically and automatically refilled, as its H_2O is used in humidification.

System Performance and Characteristics:

The physical, performance and interface characteristics of the hydrogen depolarized CO_2 concentrator are as follows:

Crew Size	= 6 Men
Design CO_2 Removal Rate	= 2.2 Lbs/Man-Day
Atmospheric Flow Rate, maximum	= 60 CFM
CO_2 Partial Pressure, maximum	= 3.0 mmHg

Table VII - H_2-DEPOLARIZED CO_2 CONCENTRATOR COMPONENTS LIST

Component	Quantity	Spares	Unit Weight Lbs.
Valve, Shutoff, Elect., Man. Override	2	1	3.0
Valve, Relief	1	1	3.0
Regulator, Pressure, Nitrogen Purge	1	2	3.0
Valve, 4-Way, Electrical	1	1	4.4
Valve, Quick Disconnect	7	5	0.5
Valve, 3-Way, Electrical, M. O.	1	1	4.6
Filter	6	4	4.6
Air Blower	2	1	14.0
Valve, Shutoff, Electrical, Liquid	1	1	2.0
H_2 Flow Sensor Controller	1	2	13.0
H_2 Flow Sensor	2	2	2.2
H_2 Transducer Controller	1	1	13.0
H_2 Transducer	2	2	0.3
Water Accumulator	1	1	2.0
H_2-Depolarized Cell Module	3	3	15.0
Sensor, Temperature, Air	2	1	0.25
Measurement Switching Unit, OCS	1	0	15.6
Measurement Unit, OCS	1	0	12.1
Valve, Solenoid, Liquid	1	1	1.0
Temperature Signal Conditioner	1	1	1.0
Subsystem Control Electronics	1	2	7.6
TOTALS	40	34	

Total Pressure, Nominal	= 14.7 psia
Total Pressure, range	= 5 to 15 psia
Air temperature	= 70 ± 5°F
Coolant air flow rate, intermittent	= 200 CFM
HDC dimensions	= 48" x 28" x 29"
Power requirement, AC	= 300 watts
Power requirements, DC	= 20 watts

Cost Estimating Relationships:

The hydrogen depolarized CO_2 concentrator system components have been grouped in five groups, designated as I through V, as shown in the system scehmatic, Figure 5. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's:

1. Process Air Blower:

The process air blower CER is primarily dependent on the electrical power input to the unit and is given by the following relation:

Process air blower fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars where, P = electrical power input to the compressor = 100 watts and W_{oc} = weight of other components = 20.69 lbs.

Substituting the values of variables in the CER yields:

$$C = 38.2 \times 77 + 2192 \times 20.69 = 48{,}293.9 \text{ dollars}$$

2. Cooling Air Blower:

The same CER used for the process air blower is applied to the cooling air blower. Thus, cooling air blower fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars where,

P = electrical power input to the air blower = 200 watts, and

W_{oc} = other components weight = 16.19 lbs.

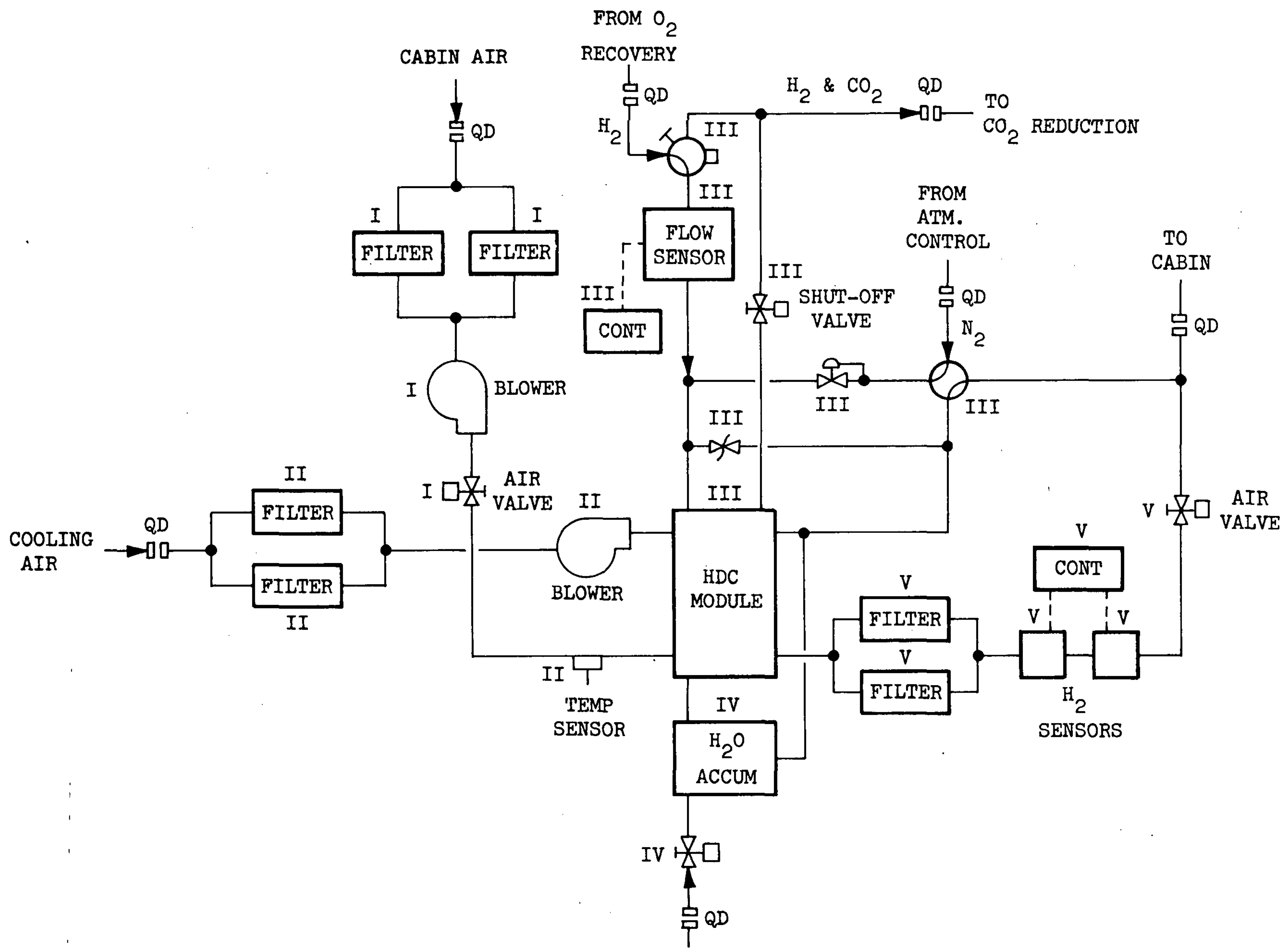

FIGURE 5. HYDROGEN DEPOLARIZED CO_2 CONCENTRATOR SYSTEM SCHEMATIC

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 148 + 2192 \times 16.19 = 41{,}142 \text{ dollars}$$

3. The Hydrogen-Depolarized Cell Module:

Study of the cost of similar electrochemical cells, manufactured for water electrolysis and electrolytic pre-treatment systems indicates that the cost of fabrication of a hydrogen depolarized cell module may be given by the following relation:

$$C = 400\ W_m + 2192\ W_{oc} + 2000 \text{ dollars}$$

where,

W_m = weight of module = 15.0 lbs., and

W_{oc} = weight of other components = 92.3 lbs.

Then,

$$C = 9000 + 262{,}322 + 2000 = 213{,}322 \text{ dollars}$$

4. Water Accumulator:

The water accumulator CER is assumed to be as follows:

The water accumulator fabrication cost $C = 18{,}6347^{0.377} + 2959\ W_{oc}$ dollars

where, V = volume of the accumulator, Ft^3, and

W_{oc} = weight of other components, lbs.

The other components denote the values associated with the operation of the accumulator. An assembly integration factor is used at the assembly level to account for necessary piping and packaging.

Substituting the values for the variables in the above equation,

where, $V = 1.0\ Ft^3$ and $W_{oc} = 5.36$ lbs.

then, $C = 18,634 + 2959 \times 5.36 = 34,494$ dollars

5. Hydrogen Sensors and Controller:

The CER used for the fabrication of hydrogen sensors and controller was based on CER's developed for similar equipment encountered in Contract NAS9-9018, and is given as follows:

Sensors and controller fabrication cost:

$$C = 4795\ (W_s + W_c + W_{oc})\ \text{dollars}$$

where,

W_s = sensor's weight = 8.8 lbs.

W_c = controller's weight = 39.0 lbs, and

W_{oc} = other components weight = 20.7 lbs.

Substituting the values of variables in the CER yields:

$$C = 4795 \times 42.5 = 203,788\ \text{dollars}$$

Integrated Hydrogen Deplarized Concentrator's Recurring CER:

The integration costs of components and assemblies into the hydrogen-depolarized concentrator system are obtained by utilizing the CER developed for the molecular sieve system, and defined in a preceeding system. Applying the said CER, then:

First unit cost $C_f = 1.833 \times 1.1 \times (48,294 + 41,142 + 213,322 + 34,494 + 203,788)$

$= 2.016 \times 541,040 = 1,097,737$ dollars

and, assuming the production of two flight-type units, one for testing and backup and the other for actual flight, then the total hardware recurring cost is given by:

$$C_T = 1,097,737 \times (2)^{1-0.1047} = 2,027,827\ \text{dollars}$$

Integrated Hydrogen Depolarized Concentrator System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breadkown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation:

System design cost C = 34,935N + 102,942 dollars

The hydrogen depolarized concentrator system comprises 21 component types as shown in Table VIII. Accordingly, system design cost C = 733,635 + 102,942 = 836577 dollars.

Values of other non-recurring cost items are listed in Table IX, which also shows the breakdown of recurring cost items based on the production of four flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE VIII- HYDROGEN DEPOLARIZED CONCENTRATOR SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	836,577	Flight Hardware Production	1,106,288
Subcontractor General and Administrative	432,332	Subcontractor G&A	186,963
Subcontractor Fee	181,559	Subcontractor Fee	78,546
Program Management	62,192	Program Management	27,657
System Engineering	263,311	Sustaining Engineering	39,827
Development Test	172,531		
Qualification Test	127,392		
Reliability Test	205,132		
AGE	925,351		
Tooling	194,098	Sustaining Tooling	34,295
Non-accountable Test Hardware	83,758		
Specifications, Vendor Coordination and Procurement Expense	683,104	Specifications, Vendor Coordination and Procurement Expense	314,186
System Integration	419,292	System Integration	144,924
Prime's Testing	409,762		
Minor Subcontracts	19,059	Minor Subcontracts	95,141
Total	5,015,450		2,027,827

Total Hydrogen Depolarized Concentrator System Cost =

5,015,450 + 2,027,827 = 8,791,665 dollars

3.3 REGENERABLE SOLID DESICCANT

Process Description:

The regenerable solid desiccant process removes CO_2 from cabin air by means of cyclic absorption/desorption in suitable granular resins. One of such resins, the GAT-O-SORB, developed by General American Transportation Corporation, was formulated by suspending sodium sarcosinate on silica gel. The chemical nature of the bonding between CO_2 and these resins provides a CO_2 removal method which is feasible for cabin P_{CO_2} levels of 3 mm Hg or less. Dynamic CO_2 absorption and desorption processes, as well as equilibrium CO_2 bed loading conditions, are extremely sensitive to the amount of water present. With the bed cooler than approximately 140°F, and water is present, the absorption process takes place according to the following relationship:

$$R * NH_2 + CO_2 + H_2O \rightarrow RNH_3^{+} + HCO_3^{-}$$

During regeneration the carbonated absorbent breaks down into fresh absorbent plus CO_2 and water. The absorption equation above shows that the regeneration molar ratio for H_2O to CO_2 is one. The corresponding weight ratio is 18/44 or 0.41. Reference 4 shows that the water collected during desorption of a prototype unit varied between 0.1 to 0.5 lb H_2O/lb CO_2. This indicates the feasibility of the method from the standpoint of maintaining adequate bed wetness.

System regeneration may be accomplished either by heating or by combined heating and evacuation to vacuum. The GAT-O-SORB unit was vacuum/thermal desorbed, and since it constitutes the only solid desiccant unit developed, further tests are required to establish the operational feasibility of thermally desorbed units.

A condensing heat exchanger is provided to dehumidify the desorbed carbon dioxide before its delivery to the accumulator. The heat transfer fluids are phased during the absorption/desorption cycle in a manner similar to that employed in cyclic molecular sieve/silica gel operation. One fundamental advantage to the solid regenerable desiccant system is that desorption requires heating fluid temperatures in the vicinity of 200°F rather than the 300°F and higher temperatures required for molecular sieve/silica gel desorption.

A schematic of the solid regenerable desiccant is shown in Figure 6. The system is comprised of the following basic components:

1) air blower,
2) two regenerable solid desiccant beds, with each bed consisting of two canisters in parallel,
3) pump,
4) accumulator, and
5) timer, manifolds and sequence control valves.

Each solid desiccant bed incorporates a plate-and-fin type heat exchanger inside the canister and in direct contact with the granules, as shown in Figure 7. A detailed listing of the components used in the system is given in Table IX.

Function of the system is as follows: cabin air is drawn by the circulation blower through the absorbing desiccant bed where the CO_2 is removed from the air which is then returned to the cabin. The CO_2 is simultaneously being evacuated by a vacuum pump from the other regenerable desiccant bed. The pump delivers the desorbed CO_2 to an accumulator for storage and subsequent delivery to the oxygen recovery system. Excess CO_2 may also be vented overboard via a relief valve.

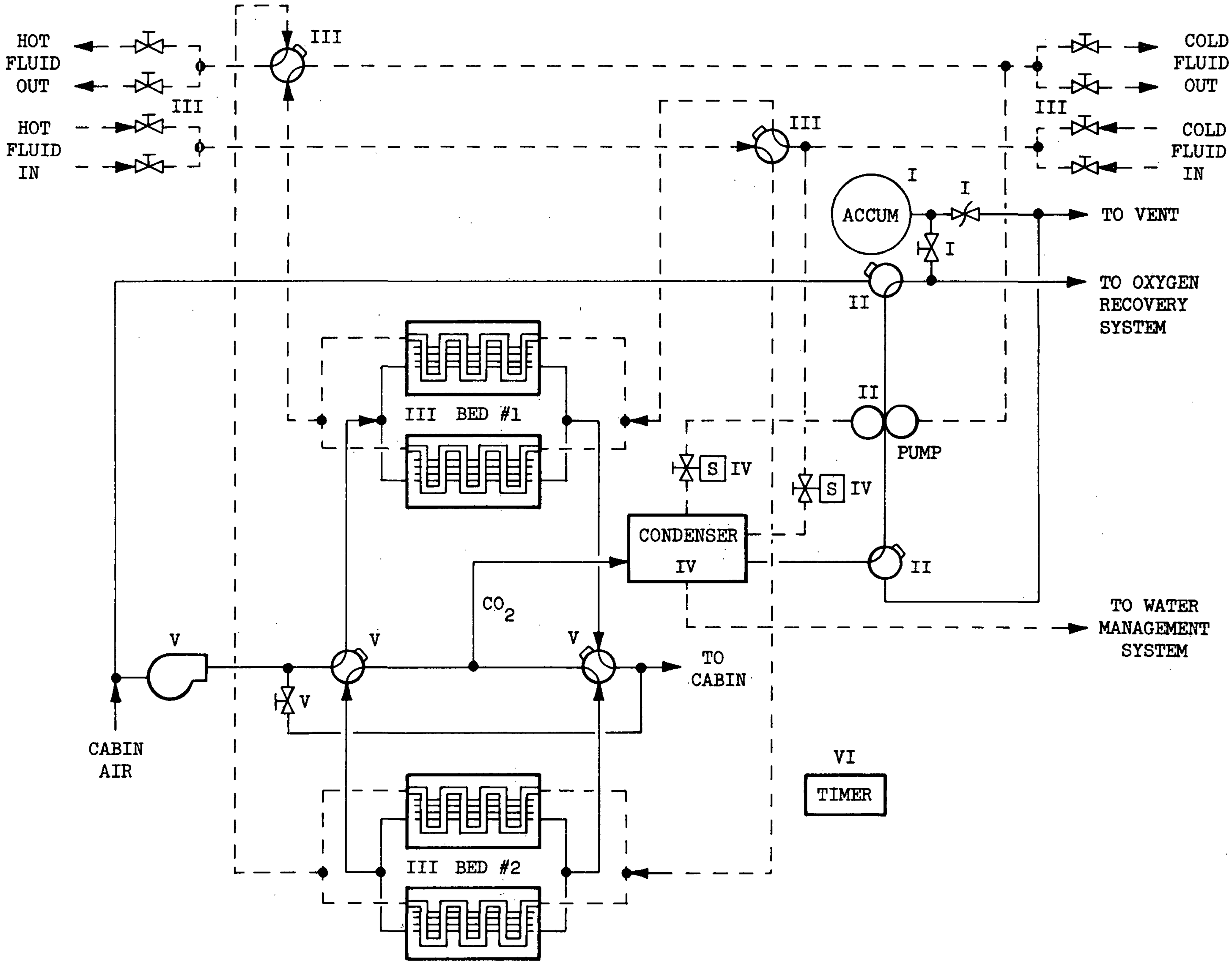

FIGURE 6. REGENERABLE SOLID DESICCANT CARBON DIOXIDE REMOVAL SYSTEM SCHEMATIC

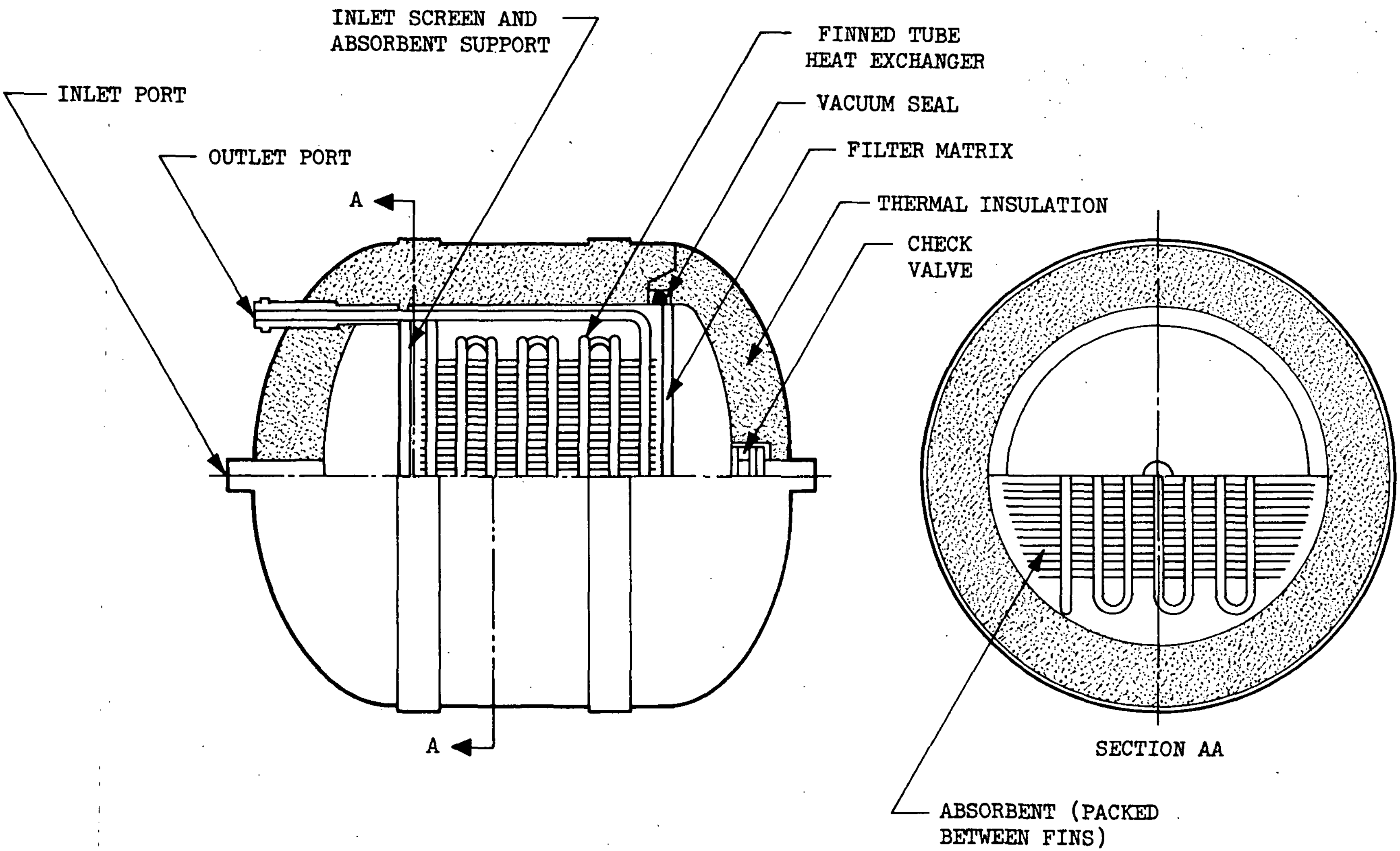

FIGURE 7. REGENERABLE SOLID DESICCANT BED CONFIGURATION

TABLE IX - REGENERABLE SOLID DESICCANT COMPONENTS LIST

COMPONENT	QUANTITY	SPARES	UNIT WEIGHT (LBS.)	UNIT WEIGHT (LBS.)
Valve, Shut-off, Manual, Low Press	1	1	2.4	4.8
Valve, Shut-off, Manual	4	3	.5	3.5
Valve, Vacuum, 3-Way, Electrical	2	3	2.0	10.0
Valve, Vacuum, 3-Way, Electrical	1	2	4.6	13.8
Valve, Shut-off, Elect., Man. Override	2	1	2.7	8.1
Valve, Vacuum, 3-Way, Manual	1	1	3.5	7.0
Valve, Press., Relief	1	1	2.5	5.0
Valve, Press., Control	1	1	2.2	6.6
Valve, 3-Way, Electrical	1	2	.7	2.1
Canister, Solid Desiccant	4	2	66.0	396.0
Blower, CO_2 Removal	1	2	14.0	42.0
Compressor, CO_2	1	3	38.0	152.0
Heat Exchanger, in absorbent beds	4	4	4.0	32.0
Heat exchanger condenser	1	0	4.0	4.0
Accumulator, CO_2	1	0	35.0	35.0
Timer	1	2	8.0	24.0
Sensor, Absorbent Bed Temperature	4	0	.1	0.4
Valve, Shut-off, Manual High Flow	8	0	3.9	0.4
Valve, 4-Way Electrical	2	2	4.4	17.6
Measurement Switching Unit, OCS	1	0	15.6	15.6
Measurement Unit, OCS	1	0	12.1	12.1
Totals	40	31	-	822.8

SYSTEM PERFORMANCE AND CHARACTERISTICS:

The physical, performance, and interface characteristics of the regenerable solid desiccant CO_2 removal system are as follows:

Crew size	= 6 Men
CO_2 Produced, average	= 2.2 Lbs/Man-Day
Design CO_2 removal rate	= 0.6 Lbs/Hr
Atmospheric Flow Rate	= 45 CFM
Air Temperature	= 75 - 90°F
Inlet CO_2 Partial Pressure	= 1.5 - 3.8 mm Hg
CO_2 delivery purity, percent	= 0.98
Coolant flow rate	= 100 Lbs/Hr
Heating fluid flow rate	= 100 Lbs/Hr
Coolant inlet temperature	= 60 - 80°F
Hot fluid inlet temperature	= 180 - 200°F
CO_2 delivery pressure to CO_2 reduction System	= 30 - 40 Psia
Electrical Power, D. C.	= 25 watts
Electrical Power, A. C.	= 620 watts
Total System Volume	= 24 Ft^3

The desorption cycle is set at 30 minutes, after which the coolant is pumped to the desorbing beds to cool them for 10 minutes before cycling to the absorption cycle. The timer then sequences the valves to divert the cabin flow through the regenerated beds and place the beds now requiring regeneration on desorption cycle. Heating fluid will then flow through the desorbing beds and the cycle is repeated. The time for a complete absorption, desorption, and cooling cycle is 80 minutes. The sequencing of the control valves is accomplished by the timer.

Cost Estimating Relationships:

The regenerable solid desiccant system components have been grouped in six groups, designated as I through VI, as shown in the system schematic, Figure 6. The recurring and nonrecurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's

1. CO_2 Accumulator:

The CO_2 accumulator is assumed to be identical to that used for the molecular sieves CO_2 removal system. The accumulator CER is given as follows:

CO_2 accumulator fabrication cost $C = 18{,}634V^{0.377} + 2959\ W_{oc}$ dollars

where, V = volume of the accumulator, Ft^3, and

W_{oc} = weight of other components, lbs.

The other components denote the valves associated with the operation of CO_2 accumulator. An assembly integration factor is used at the assembly level to account for necessary piping and packaging.

Substituting the values for the variables in the above equation, where $V = 9.1\ Ft^3$ and $W_{oc} = 4.5$ lbs., yields:

$$C = 18,632 \times 2.3 + 2959 \times 4.5 = 56,169 \text{ dollars}$$

2. CO_2 Compressor:

The influencing parameter in the CO_2 compressor fabrication is the electrical power input to the unit. The CER is given as follows:

CO_2 compressor fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars

where, P = electrical power input to the compressor, watts, and

W_{oc} = weight of other components, lbs.

for the CO_2 compressor,

$P = 420$ watts, and

$W_{oc} = 2.1$ lbs.

Substituting these values in the above equation yields the following:

$$C = 38.223 \times 300 + 2192 \times 2.1 = 16070 \text{ dollars}$$

3. Regenerable Solid Desiccant Canisters:

The regenerable solid desiccant canisters incorporate built-in plate-and-fin heat exchangers. The solid desiccant canister CER thus includes elements for the canister itself, the built-in heat exchanger and the associated valves. The CER is given as follows:

$$\text{Canister fabrication } C = 158.65\ (100\ W_{can}^{\ 0.267} + W_{HX}^{\ 0.267}\ N_p^{\ 1.905})$$

$$Q^{0.89} + 2959\ W_{oc} \text{ dollars}$$

where, W_{can} = average canister weight = 16.5 lbs.

W_{HX} = heat exchanger weight = 4.0 lbs.,

N_p = number of ports per heat exchanger = 2

Q = number of units used = 4, and

W_{oc} = other components weight = 31.2 lbs.

then,

$$C = 158.65\ (100 \times 2.12 + 1.45 \times 3.75) \times 3.43 + 2959 \times 31.2$$
$$= 158.65 \times 217.44 \times 3.43 + 92{,}320$$
$$= 118{,}085 + 92{,}320 = 210{,}405 \text{ dollars}$$

4. Heat Exchanger Condenser

The following CER is used to evaluate the heat exchanger condenser fabrication cost:

$$C = 159\ W^{0.267}\ N_p^{\ 1.905} + 2959\ W_{oc} \text{ dollars}$$

where,

W = heat exchanger weight = 4.0 lbs.
N_p = number of ports per heat exchanger = 4, and
W_{oc} = weight of other components = 8.1 lbs.

Substituting the values of the variable in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 8.1 = 27{,}207 \text{ dollars}$$

5. Air Blower:

The same CER used for the CO_2 compressor is applied to the air blower. Thus, air blower fabrication cost $C = 38.2P^{\ 0.942} + 2192\ W_{oc}$ dollars,

where,

P = electrical power input to the air blower = 200 watts, and

W_{oc} = other components weight = 17.6 lbs.

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 148 + 2192 \times 17.6 = 44{,}239 \text{ dollars}$$

6. Timer and Controls:

The CER used for the timer and associated controls fabrication cost was based on CER's for similar equipment encountered in Contract NAS9-9018, and is given as follows:

Time and controls fabrication cost $C = 4795\ (W + W_{oc})$ dollars,

where,

W = timer weight = 8.0 lbs., and

W_{oc} = other components weight = 20.0 lbs.

substituting the values of variables in the CER yields:

$$C = 4795 \times 28 = 134{,}260 \text{ dollars}$$

<u>Integrated Regenerable Solid Desiccant System's Recurring CER</u>:

The integration costs of components and assemblies into the regenerable solid desiccant system are obtained by utilizing the system's recurring CER defined for the molecular sieve system, defined above. Applying the said CER, then:

$$\begin{aligned}\text{First unit cost } C_F &= 1.833 \times 1.1 \times (56{,}169 + 16{,}070 + 210{,}405 + \\ &\quad 27{,}207 + 44{,}239 + 134{,}260) \\ &= 2.016 \times 488{,}350 \\ &= 984{,}514 \text{ dollars}\end{aligned}$$

and, assuming the production of two flight-type units, one for testing and backup and the other for actual flight, then the total hardware recurring cost is given by:

$$CT = 984{,}514 \times (2)^{1-0.1047} = 1{,}823{,}960 \text{ dollars}$$

Integrated Regenerable Solid Desiccant System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breakdown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

System design cost $C = 34{,}935N + 102{,}942$ dollars

The regenerable solid desiccant system comprises 21 component types as shown in Table IX. Accordingly, system design cost $C = 733{,}635 + 102{,}942 = 836577$ dollars.

Values of other non-recurring cost items are listed in Table X, which also shows the breakdown of recurring cost items based on the production of four flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE X - REGENERABLE SOLID DESICCANT SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	836,577	Flight Hardware Production	995,152
Subcontractor General and Administrative	432,332	Subcontractor G&A	168,169
Subcontractor Fee	181,559	Subcontractor Fee	70,770
Program Management	62,192	Program Management	24,806
System Engineering	263,311	Sustaining Engineering	33,750
Development Test	172,531		
Qualification Test	127,392		
Reliability Test	205,132		
AGE	925,351		
Tooling	194,098	Sustaining Tooling	30,825
Non-accountable Test Hardware	83,758		
Specifications, Vendor Coordination and Procurement Expense	683,104	Specifications, Vendor Coordination and Procurement Expense	282,531
System Integration	419,292	System Integration	130,413
Prime's Testing	409,762		
Minor Subcontracts	19,059	Minor Subcontracts	85,544
Total	5,015,450		1,823,960

Total Regenerable Solid Desiccant System Cost = 5,015,450 + 1,823,960 = $6,839,410

Section 4

CONCLUSIONS

Methodology and cost estimating relationships, for flight-type and prototype CO_2 concentrators, have been developed and presented. The study results are based on the assumption that feasibility and advance technology requirements of the systems, including possibly some manned testing, have been achieved. This assumption is fulfilled only for the molecular sieves concentrator where one system has undergone continuous 60 days of manned testing. Additional development is required to bring the other two concentrator types to the same status.

A validity check was made by comparing the molecular sieves system considered here and that developed for Skylab. The system evaluated here is twice the size of the Skylab system and is also more complex as it desorbs CO_2 thermally and stores it in an accumulator, while the Skylab system is desorbed to vacuum with all the previously adsorbed CO_2 and moisture being vented overboard. The cost estimates developed in this report were found to be approximately 50 to 70% higher than the actual cost of the Skylab unit. Considering the example evaluated and its results indicates that the methodology used is valid and the cost estimates are reasonably accurate. However, the restricted amount of actual cost data available and the complexity of other systems indicate that additional data are required in order to establish a higher level of confidence in the developed CER's.

Areas where additional efforts are warranted include the following:

1. The completion and manned testing of the six-man hydrogen-depolarized concentrator currently under development for the SSP Program.
2. The development of thermal desorbed regenerable solid desiccant CO_2 collection system.
3. The collection and analysis of additional CO_2 concentrator cost data, such as that from the SSP Program.

4. The inclusion of cost elements pertaining to operating system parameters, such as power, heat rejection, expendables, subsystem interfaces, and crew time, to cost estimating relationships so that all the systems considered would be compared on a common basis encompassing all the penalties incurred by each system on the spacecraft for the duration of the mission. For example, the hydrogen-depolarized concentrator is lighter, smaller, less expensive, requires no heating fluid loop, and is capable of maintaining a lower CO_2-level concentration than the molecular sieves unit. However, the HDC consumes daily expendables of hydrogen and oxygen while the molecular sieves concentrator requires no expendables. Thus, system comparisons will be meaningful only if all the penalties incurred by each system are taken into consideration.

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